Ground penetrating radar as part of a holistic strategy for inspecting trackbed

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SUMMARY

Significant changes can occur at different stages in the lifetime of a ballasted trackbed under repeated loading. These include but are not limited to the generation of fines which may clog ballast void space, the failure of the formation leading to ingress of fines through pumping and localised settlement of the formation leading to the growth of ballast pockets.

Traditional trackbed inspection strategies based on visual patrols and track geometry measurements are generally late indicators of subgrade and ballast quality related issues. They can also be misleading resulting in inappropriate and cost inefficient maintenance.

Monitoring ballasted trackbed with ground penetrating radar (GPR) allows decisions to be made on timely and cost effective maintenance interventions. Combining track geometry measurements with GPR provides unique condition-based information to plan a holistic ballast and trackbed management strategy.

Significant elements of this strategy include:

- Effective integration of GPR (subsurface) and track geometry (surface) trackbed metrics, and
- Generation of exception reports for trackbed condition including ballast fouling and formation failure.

The benefits of this approach are multifold:

- Accurate prioritisation of problem trackbed and delineation of the extent of remedial works required,
- Reduction in the number of trial holes and duration of line blocks, required to investigate sites,
- Deployment of ballast handling, tamping and cleaning machines to where they are most needed,
- Savings in ballast resource by optimising redistribution,
- Reduction in the number of interventions during the life of the ballast through condition-based planning, and
- Monitoring the performance of ballast maintenance crews.
1. INTRODUCTION

Ballast trackbed is by far the most commonly used type of railway construction around the world. The ballast layer is designed to absorb much of the impact and dynamic energy of a passing train and to distribute the loading force evenly over the formation layer to preserve a smooth ride. It is important that the ballast layer remains free of fines. As a general rule of thumb, the more fines the less elastic the ballast layer becomes and the more susceptible it will be to retain water thus reducing its bearing capacity. Contaminated ballast causes an unstable pressure distribution on the subgrade.

An uncontaminated free draining ballast layer at the required thickness is a critical component of a stable and safe trackbed. Track geometry measurements determine the position of the rails in space. A significant departure from the designed geometry indicates the presence (not the cause) of an unstable trackbed and instigates trackbed maintenance such as tamping to recover alignment. Repeat track geometry exceedances may require trial pit investigation to determine the root cause of the problem, which may extend beyond the limits of the measured anomaly. Visual patrols are often used in addition to track geometry to help identify problem areas but these too only target surface manifestations of trackbed problems; problems which are consistently associated with causes at depth (Figure 1). Visual patrols are especially problematic with ballast contamination often hidden from view or the actual extent of visible contamination not being determinable.

Ground penetrating radar (GPR) such as Zetica’s Advanced Rail Radar (ZARR) system is a proven technology for mapping changes in the actual thickness and quality of the ballast and deeper trackbed layers across a network [1,2,3,8]. Combining track geometry measurements with GPR provides unique condition-based information to plan a holistic ballast and cost effective trackbed management strategy.

Figure 1: Iceberg analogy
The data obtained from a GPR survey is summarised in terms of information that can be obtained on the thickness and depth of identifiable trackbed interfaces, so called ‘layer metrics’, and information on the quality of the ballast layer, in the form of a ballast fouling index.

Trackbed interfaces are manifested as a linear reflection within the GPR data and will only occur where there is a contrast in the electrical properties of the materials either side of the boundary, such as between a clean ballast layer and subgrade or clean ballast and a fouled ballast layer. The GPR-derived fouling index is based on measurement of the level of signal scattering within the ballast layer and is independent of the ballast layering.

1.1 GPR-derived layer metrics

Examples of layer metrics derived from GPR data include the following:

- Ballast depth exceedance (BDE) represents a measure of how well the thickness of the primary trackbed layer conforms to a customer-specified design thickness. A minimum ballast thickness is required below the sleepers in order to provide correct support to the track and adequate drainage.

- The Layer Roughness Index (LRI) indicates the degree of variance in the thickness of the primary trackbed layer over a specified length (for example, 5m and 20m). The LRI is designed to highlight areas where the thickness of the layer is changing rapidly. Such rapid variations can be an indication of sub-grade failure or wet bed formation (Figure 3).
1.2 GPR-derived ballast fouling

As detailed in Zhang et al [8], Zetica has developed a method to derive a continuous ballast fouling index (BFI) from the GPR data, based on analysis of the signal scattering response observed using a high frequency antenna (2GHz). Calibration of the output to industry standard fouling indices has achieved through detailed ballast sampling and particle size distribution (PSD) analysis. The BFI has been calibrated to Selig’s Fouling Index in the USA (Figure 4) and has recently been calibrated to Queensland National’s Percentage Voids Contamination (PVC) index. The latter is considered more suitable in situations where the ballast fouling is predominantly associated with coal fines and dust.
1.3 Combined GPR and track geometry

Combining the GPR derived indices with track geometry data provides an efficient means of identifying those track geometry faults that are associated with an underlying measurable trackbed problem and helping determine the extent of that problem. It can also highlight areas of moderate or poor trackbed integrity that may not yet be manifested as a track geometry fault.

Methods of combining the datasets can be as simple as a graphical plot (Figure 5), which can be used by the track engineer to manually identify correlations, or development of a combined index such as the QI2 index designed for Irish Rail following a detailed GPR survey of the Dublin-Cork line in 2008.

The QI2 index comprises a simple rules matrix (Table 1) that combines the track geometry quality index results with a combined track quality index (CTQI) derived from a set of GPR layer and fouling metrics. The QI2 index is weighted in favour of the track geometry results to ensure that any severe pre-existing track geometry faults are highlighted (i.e. a track geometry QI index of 1 is unaffected by the CTQI index). The results are commonly presented in the form of track charts, which allow problem sections of track to be easily identified (Figure 6).
**Figure 5:** Report with data panels showing (top-bottom) – layers in the center, layers over the shoulders, a contoured map of depth to fouled ballast/formation, colour strip charts showing moisture index, thickness of ballast against defined thresholds, and ballast layer roughness, 2D BFI plots, colour strip charts of the 1D BFI, and track geometry (Top Up and Down + Twist). Linear meterage and GPS coordinates provided.

**Table 1:** QI2 rules matrix
1.4 Work Order Recommendation (WOR)

This unique deliverable is a rules-based method for determining where and how to treat the trackbed, based on combining the GPR-derived metrics (layer and BFI) with the track geometry data. Each of the rules matrices can customised according to a customer’s method of working. Customisations might include the specification of fouling intervention levels for undercutting and shoulder cleaning and setting the ballast depth exceedence threshold to ensure that undercutting is only carried out where the ballast layer thickness is sufficient.

Currently five maintenance types are included:

- Undercutting (ballast cleaning)
- Shoulder Cleaning
- Tamping
- Track Reconditioning
- Drainage Works

The maintenance types can be mutually independent or exclusive.

Output formats include summary tables detailing the total length of each recommended maintenance type within the surveyed area (Table 2), detailed or simplified maintenance planning track charts (Figure 8, upper panel) and Google Earth KML/KMZ files (Figure 8, lower panel).

<table>
<thead>
<tr>
<th>Maintenance Type</th>
<th>Total (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undercutting</td>
<td>2.97</td>
</tr>
<tr>
<td>Shoulder Cleaning (left)</td>
<td>0.36</td>
</tr>
<tr>
<td>Shoulder Cleaning (right)</td>
<td>0.13</td>
</tr>
<tr>
<td>Track Reconditioning</td>
<td>4.71</td>
</tr>
<tr>
<td>Drainage Work</td>
<td>3.07</td>
</tr>
<tr>
<td>Tamping</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 2: Tabulated WOR summary showing totals for each maintenance type.
2. BENEFITS

2.1 UK

Network Rail in the UK have reported significant improvements to their track renewals process with a reduction in unnecessary ballast replacement (1 in 15 sites), reduction in the number of trial holes (50% targeted), the application of more appropriate remedial actions (Figure 9) and fewer pre-mature failures. Current work is being directed at using ZARR to predict rates of return from ballast cleaners and help determine the residual life of ballast.

Figure 9: Trackbed renewal as planned using track geometry only (top) and after revision based on including GPR (bottom).
2.2 Irish Republic

For Irish Rail, GPR provides an important tool which is being proactively used to allow focused planning of trackbed remediation works on those areas most in need of rehabilitation. This allows an optimisation of available budgets and is thus a cost-effective tool in the trackbed remediation programme. Subsequent measurement of track quality following the targeted remediation works to the trackbed, have resulted in significant improvements to the measured track quality. The information provided by GPR and track geometry has also been used as part of localised re-ballasting programmes undertaken in advance of warm weather (in those areas that have not yet formed part of the remediation program) to offset the specific safety risks associated with track behaviour in warm weather due to a lack of ballast. Overall, the undertaking of the GPR survey on the Dublin-Cork line has provided Irish Rail with valuable insights into the condition of the ballast and sub-ballast layers which were previously unknown. The continuity of the survey and its results allows Irish Rail to manage the Dublin-Cork line on a whole route basis thus ensuring the application of prioritized cost effective solutions.

2.3 North America

In North America ZARR is providing an accurate and objective indication of priority areas for ballast cleaning across a railroad’s network. The combination of trackbed centreline and shoulder GPR data enables decisions to be made on whether to only shoulder clean, with cheaper dedicated shoulder cleaners or whether to treat the whole trackbed with more expensive undercutters. The results are statistically summarised per sub-division (Figure 10) to help prioritise maintenance budgeting across the network.

![Figure 10](image)

**Figure 10:** In this example Category 1-5 represents relatively very fouled to clean ballast respectively for GPR scans of both shoulders and the centre. Division 1 has a greater proportion of highly fouled ballast (Category 2) compared with Division 2, which has a predominance of moderately fouled (Category 3) to moderately clean (Category 4) ballast.
The integration of GPR and track geometry is also being used in the USA to help determine the cause of localised track geometry faults. Persistent faults result in costly slow orders being imposed on high revenue track. In the example below (Figure 11) GPR has identified the lateral and depth extent of a subsidence zone across an embankment. This information is invaluable in designing an effective remediation program.

Figure 11: Integrated 3-channel GPR survey showing the contoured base of ballast (5th panel) to identify the cause of a track geometry curvature anomaly (6th panel) and the limits of remedial works required. Other information shown includes fouling and layer roughness metrics.
3. CONCLUSIONS

The growth in freight rail tonnage and associated increase in the cost of occupying track for routine inspection and maintenance is necessitating a change in the maintenance planning paradigm. Data from multi-sensor survey platforms including GPR and track geometry, when integrated as part of a holistic strategy for prioritising and planning appropriate maintenance, has been shown to provide unique condition-based information and significant cost savings.

REFERENCES


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